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Effects of Increasing Rainfall Depths and Impervious Areas on the Hydrologic Responses

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Abstract

Hydrologic modeling is a popular tool for estimating the hydrological response of a watershed. However, modeling processes are becoming more complex due to land-use changes such as urbanization, industrialization, and the expansion of agricultural activities. The primary goal of the research was to use the HEC-HMS model to evaluate the impact of impervious soil layers and the increase in rainfall-runoff processes on hydrologic processes. For these purposes, the Watershed Modelling System (WMS) and Hydrologic Engineering Center's-Hydrologic Modeling System (HEC-HMS) models were used in this study to simulate the rainfall-runoff process. To compute runoff rate, runoff volume, base flow, and flow routing methods SCS curve number, SCS unit hydrograph, recession, and loss routing methods were selected for the research, respectively. To reduce the processing time and computational complexity, a small section of the Pipestem Creek Watershed was selected to understand the methods and concepts associated with the hydrologic simulation model building. A DEM along with other required data such as land use land cover data, soil type data, and meteorological data was utilized to delineate the watershed in WMS. The output of WMS was utilized to run the HEC-HMS model for five different scenario analyses. All the relevant data were plugged in to the model to get the desired map. Subsequently, outlets at appropriate locations were selected for the sub-basin delineation for further analysis. Finally, the model was parametrized to get successful simulation results. Overall, peak discharges and runoff volumes were increased with increasing storm depths and impervious areas. Peak discharges were increased to 36% and 51% when rainfall depths were increased by 10% and 20% from the initial rainfall depth, respectively. Runoff volumes were also increased to 35% and 49% for the same scenarios, respectively. Peak discharges were increased to 12% and 78% with a 10% and 20%, respectively, increase in impervious areas. The runoff volumes were increased by 12% and 76% when impervious areas were increased by 10% and 20%, respectively. The simulation models responded well, and the peak discharges and runoff volumes increased with increasing storm depths and impervious areas.

Keywords

Peak Discharge, Runoff, Impervious Area, HEC-HMS, WMS

1. Introduction

In hydrology, modeling is a widely used technique for estimating how a basin will respond to the different rainfall events. There are many factors contributing to the complexity of the modeling process, such as climate change, urbanization, and the expansion of agricultural activities. Therefore, scientists and researchers all over the world are trying to develop accurate tools for modeling hydrologic processes. With the advancement of computer technology and the availability of near-real-time precipitation data, rainfall-runoff models are expected to be able to predict runoff in a more accurate manner than they did in the past [1]. Watershed Modeling System (WMS) and Hydrologic Engineering Center's Hydrologic Modeling System (HEC-HMS) are two powerful hydrologic modeling tools. These two tools enable watershed modeling to be completed at all stages, including delineation of watersheds and subbasins, computation of geometric parameters, computation of hydrologic parameters (curve number, time of concentration, rainfall depth, losses, baseflow, runoff transformation, and routing), and visualization of the results [2].

HEC-HMS model has also been used for simulating rainfall-runoff processes [3] [4] [5] with geo-informatics and atmospheric models for flood forecasting in different regions of the world [6] [7] [8]. The model was found accurate in spatially and temporally predicting watershed responses in event based and continuous simulation, as well as simulating various scenarios in snow-melt [9], flood forecasting [10] [11], and early flood warnings [12]. The main objective of the study was to assess the increase of rainfall-runoff processes and impervious soil layers on hydrologic processes using the HEC-HMS model. This research analyzed the effects of three increased hypothetical rainfall events and urbanization/industrialization (in terms of impervious areas) scenarios in a rural basin of North Dakota using the HEC-HMS simulation model.

2. Materials and Methods

2.1. Study Area

Pipestem Creek watershed was selected for the study, which is located in Wells County, in the southern part of North Dakota, USA (**Figure 1(a)**). The 8-Digit Hydrologic Unit Code (HUC) of Pipestem is 10,160,002, and this watershed

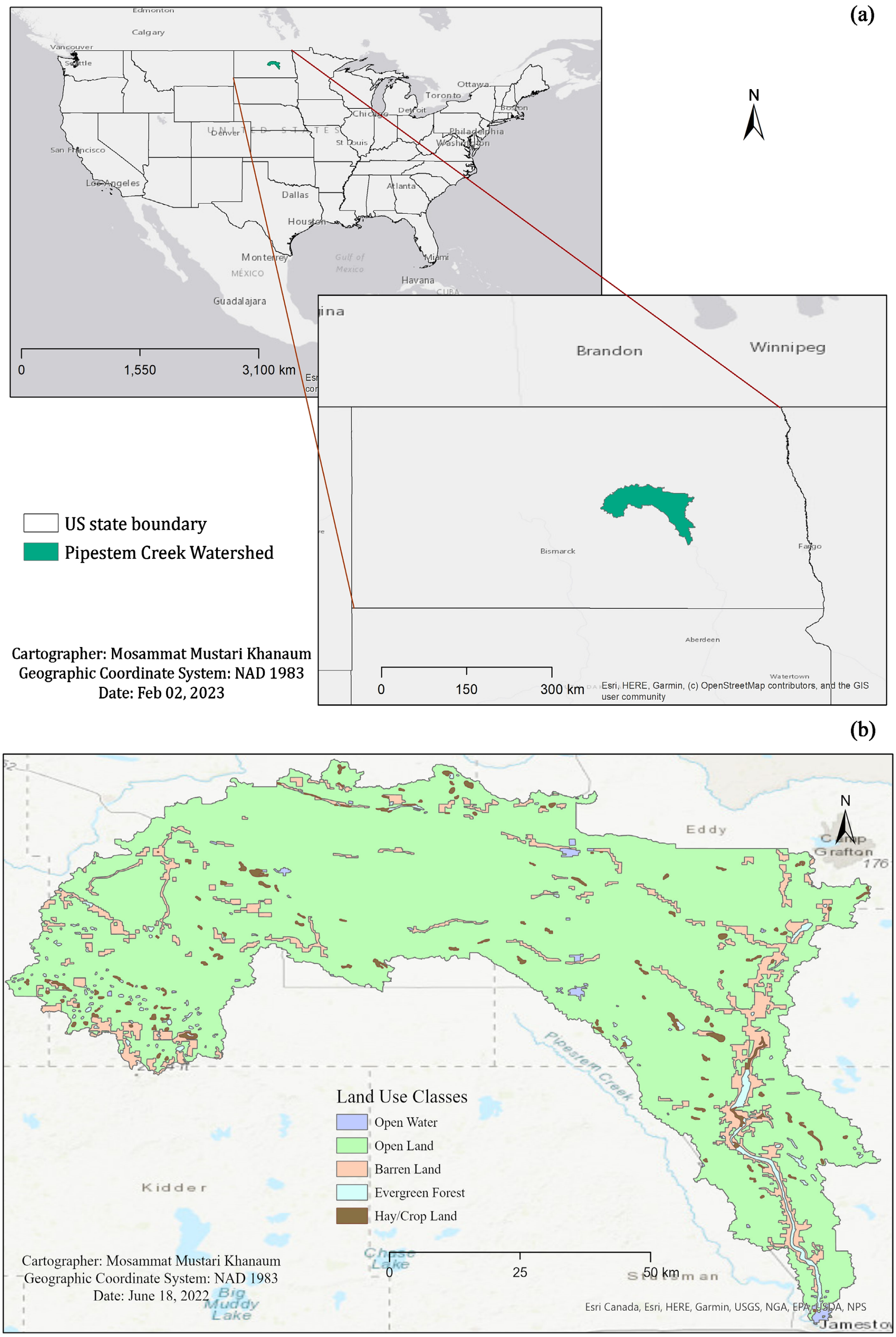

Figure 1. (a) Location of Pipestem Creek watershed; (b) Land use classes of the study area.

(sub-basin) is approximately 2571 km^2. The land use pattern of the area is predominantly open/fallow/barren land followed by evergreen forest and crop land (**Figure 1(b)**). This sub-basin encompasses commodities ranging from soybeans, wheat, barley, corn, canola, sunflowers, and field peas to feed beef cattle, swine, poultry, and bees. The drainage patterns flow to the southeast, ending at the Pipestem Reservoir near the city of Jamestown. In this area, the total length of Rivers/Streams[1] is 851 km, and the surface of Lakes/Reservoirs is 15 km^2. The study area is fairly flat, which allows researchers to effectively investigate the effect of varying levels of storm depths and impervious areas on watershed properties such as peak discharges and runoff volumes.

2.2. HEC-HMS Hydrological Model

HEC-HMS is a widely used hydrologic modelling software developed by the US Army Corps of Engineers. It is a physically based and conceptual semi-distributed model designed and implemented for simulating the rainfall-runoff processes in a different range of geographic areas including large river basin water supply and flood hydrology to small urban and natural watershed runoff [13]. The system incorporates losses, runoff transform, open channel routing, analysis of meteorological data, rainfall-runoff simulation, and model parametrization. The HEC-HMS links separate models to represent each component of the runoff process, such as models that compute runoff volume, models of direct runoff, and models of base flow. Each model run combines a basin model, a meteorological model, and control specifications with run options to obtain results. Several methods were selected for each component of the runoff process, including runoff depth, direct runoff, baseflow, and channel routing, as shown in the flow chart (**Figure 2**).

All the operations, such as watershed delineation, flow accumulation, flow direction, and CN calculation, were performed sequentially, following and consulting the WMS and HEC-HMS user manuals [14] [15].

2.3. Scenarios Tested for Simulation Responses

In this study, the hydrologic responses were evaluated for increasing rainfall depths and impervious areas (due to urbanization and industrialization). Five different scenarios were run in the HEC-HMS model to determine the peak discharge, runoff volume, and hydrographs at the final outlet and sub-basin 4 for a 100-years Type II storm event (**Table 1**).

2.4. Evaluation Methods

Hydrographs and summery tables were examined, and Excel graphs were used to show the changes (trends) in peak discharges and volumes that occurred with increasing rain depths and impervious areas due to urbanization and industrialization. Additionally. percent changes with increasing rain depths and impervious

[1]ND Department of Health, 2006, https://deq.nd.gov/WQ/3_Watershed_Mgmt/SWDataApp/viewer/index.html.

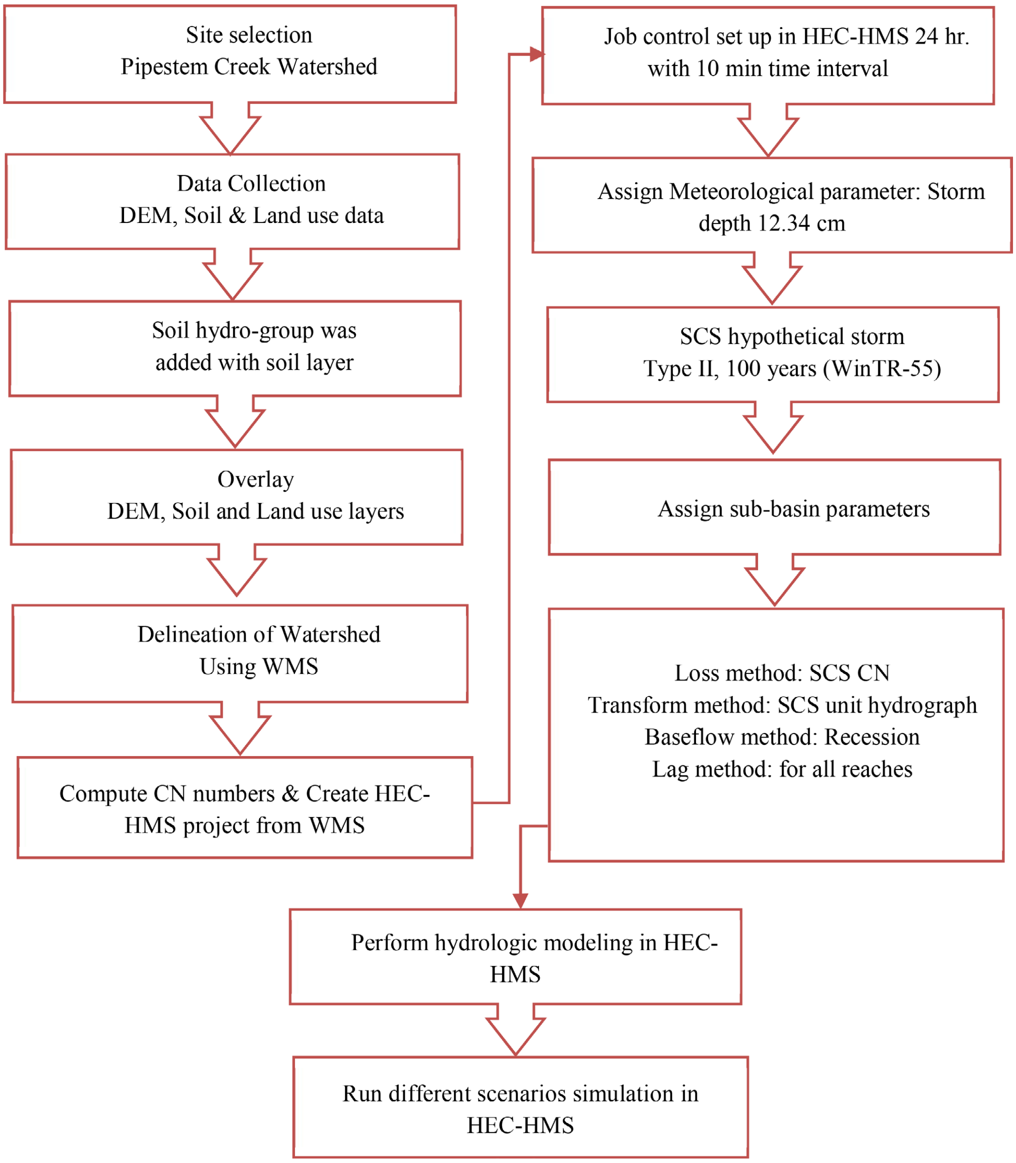

Figure 2. Flow chart of the modelling process.

Table 1. Description of model simulations for different scenarios.

Model Simulation	Location	Storm Depth (cm)	Soil impervious layer
Scenario-1	Final outlet	12.34	0%
Scenario-2	Final outlet	13.46	0%
Scenario-3	Final outlet	14.73	0%
Scenario-4	Sub-basin 4	12.34	10%
Scenario-5	Sub-basin 4	12.34	20%

areas were also reported. The percent change was calculated using the following relationship:

$$\text{Percentage change} = \{\text{Absolute}\ (Q_{initial} - Q_{final})/Q_{initial}\} * 100\% \quad (1)$$

where, $Q_{initial}$ = Peak discharge at initial rainfall of 12.34 cm (100 years Type II storm).

Q_{final} = Peak discharge at 13.46 cm and 14.73 cm (10% and 20% more respectively) rainfall from 12.34 cm.

3. Results and Discussion

All required data were collected for different federal and state agencies. The Digital Elevation Model (DEM) of the watershed (**Figure 3(a)**) was obtained from the USGS Map Viewer[2]. The land use and land cover data (*Statsgo* soil data) were obtained from the NRCS Geospatial soil data gateway, Web Soil Survey[3]. Afterward, DEM and shape files were imported, and different cartographic maps were created in ArcGIS Pro V2.9.1. The flow directions and flow accumulations were determined using Run Topaz function in WMS, and the watershed was divided into five sub-basins.

HEC-HMS Model Layout and Simulation Results

Figure 4 shows the layout of the HEC-HMS model. **Tables 2(a)-(e)** show the simulation outputs such as the global summary at the final outlet (junction 12C) of the watershed for different scenarios. **Figure 5** illustrates the hydrograph at the final outlet for Scenario-5.

The simulation models responded well with increasing rainfall amount and impervious areas, as presented in **Tables 2(a)-(e)**. In the scenario-1 with storm depth of 12.34 cm for 100-years storm and with zero impervious areas, the simulated peak discharge and runoff volume were 157 m^3/s and 2.7 cm, respectively. In scenarios 2 and 3 with 10% (13.46 cm) and 20% (14.73 cm) increase in storm depths, the corresponding peak discharges and runoff volumes were 214 m^3/s and 3.63 cm, and 237 m^3/s and 4.0 cm, respectively. Overall, peak discharges increased to 36% and 51% when rainfall depths increased by 10% (Scenarios-4) and 20% (Scenarios-5), respectively (**Figure 6**). Similarly, the runoff volumes increased to 35%, and 49% when rainfall depths increased by 10% (Scenarios-4) and 20% (Scenarios-5), respectively (**Figure 7**). The findings of this study are in agreement with the results of some other previous studies [16]. Overall, runoff volume was found to increase with increasing storm depths and thus showed a positive correlation with storm depths.

Similarly, the Scenario-1 with storm depth of 12.34 cm for 100-year storm and zero impervious areas, was compared with scenarios 4 and 5, which had a 10% and 20% increase in impervious areas due to assumed urbanization and industrialization (**Table 3**). The peak discharges increased to 12% and 78% when impervious areas increased to 10% (Scenarios-4) and 20% (Scenarios-5), respectively (**Figure 8**). Similarly, the runoff volumes were increased to 12%, and 76% when impervious areas increased to 10% (Scenarios-4) and 20% (Scenarios-5), respectively (**Figure 9**). Like storm depths, the runoff volume was found to in

[2]USGS Map Viewer https://apps.nationalmap.gov/downloader/#/.

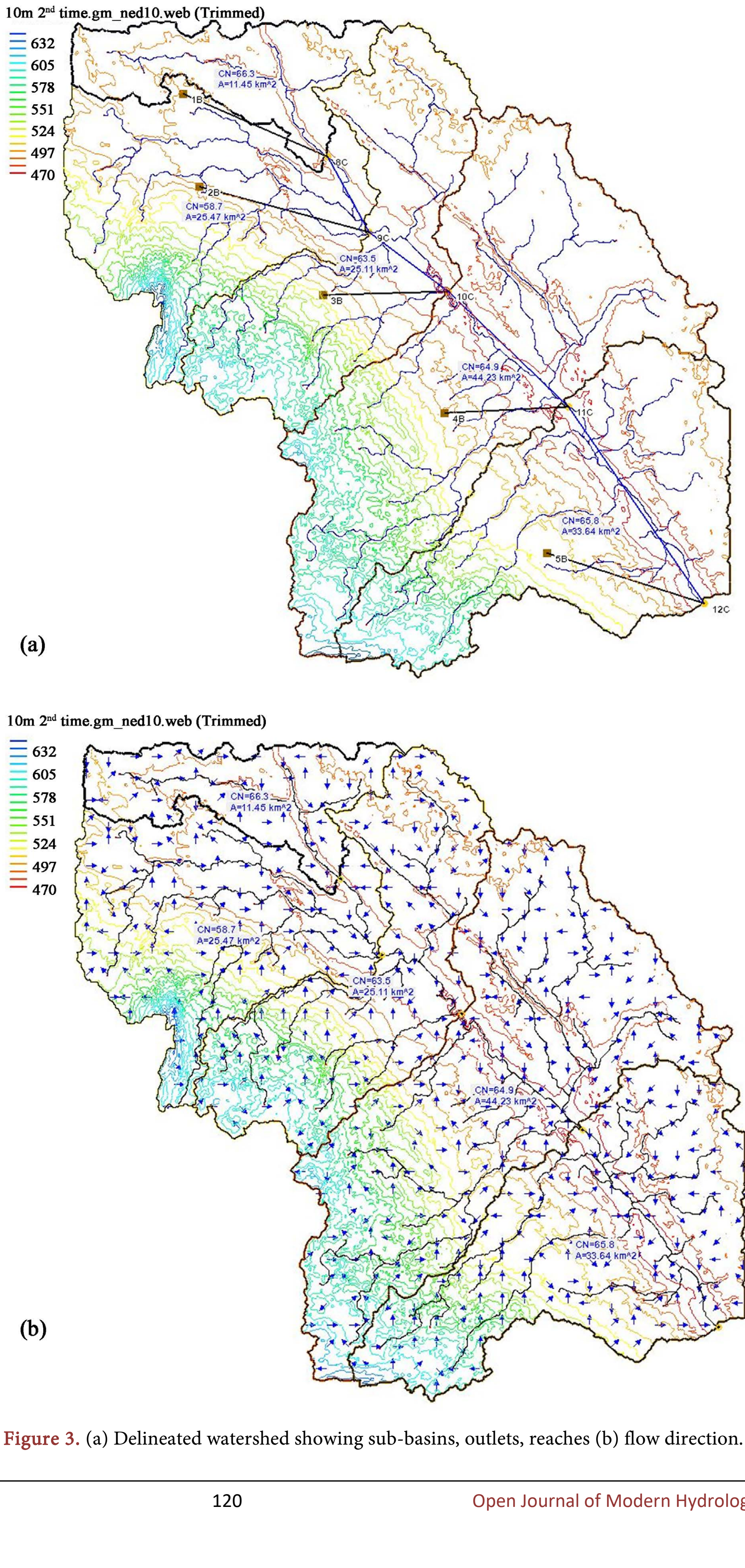

Figure 3. (a) Delineated watershed showing sub-basins, outlets, reaches (b) flow direction.

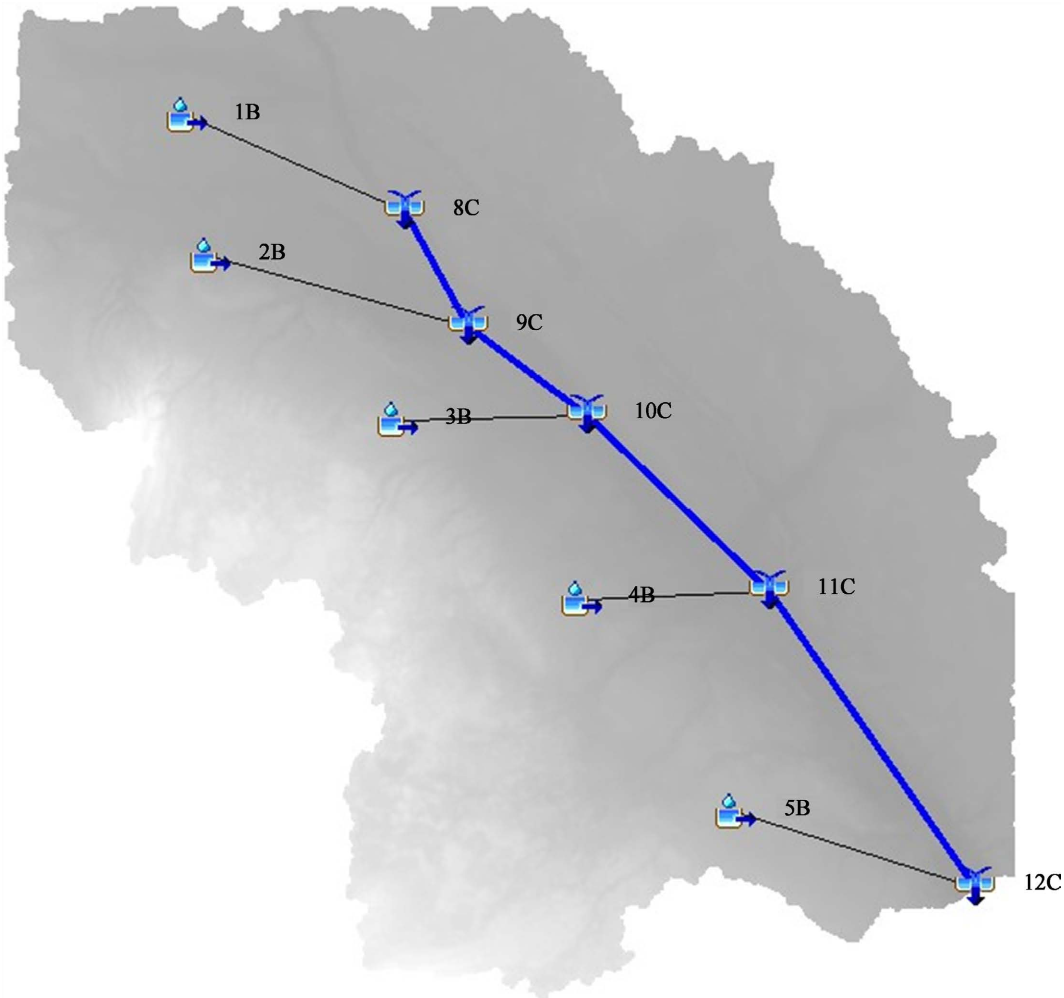

Figure 4. Layout of the HEC-HMS model.

Table 2. (a) Global Summary for Scenario-1 at final outlet (12C); (b) Global Summary for Scenario-2 at final outlet (12C); (c) Global Summary for Scenario-3 at final outlet (12C); (d) Global Summary for Scenario-4 at final outlet (12C); (e) Global Summary for Scenario-5 at final outlet (12C).

(a)

Hydrologic Element	Drainage Area (km^2)	Peak Discharge (m^3/s)	Time pf Peak	Volume (cm)
1B	29.65	47.92	26 May 2017, 19:00	6.48
2B	65.96	22.53	27 May 2017, 01:00	2.05
3B	64.79	34.15	26 May 2017, 22:45	2.87
4B	114.54	44.83	27 May 2017, 00:30	2.32
5B	87.12	30.18	27 May 2017, 03:00	2.30
8C	29.65	47.92	26 May 2017, 19:00	6.48
9C	95.61	62.49	26 May 2017, 20:15	3.43
10C	160.64	93.97	26 May 2017, 21:00	3.20

Continued

11C	275.18	133.50	26 May 2017, 21:45	2.83
12C	362.30	157.31	26 May 2017, 23:00	2.70
8R	29.65	47.92	26 May 2017, 19:00	6.48
9R	95.61	62.49	26 May 2017, 20:15	3.43
10R	160.64	93.97	26 May 2017, 21:00	3.20
11R	275.18	133.50	26 May 2017, 21:45	2.83

(b)

Hydrologic Element	Drainage Area (km^2)	Peak Discharge (m^3/s)	Time pf Peak	Volume (cm)
2B	65.96	28.43	27 May 2017, 00:45	2.58
1B	29.65	55.11	26 May 2017, 19:00	7.43
10R	160.64	113.14	26 May 2017, 21:00	3.85
11C	275.18	184.04	26 May 2017, 21:45	3.88
10C	160.64	113.14	26 May 2017, 21:00	3.85
9R	95.61	74.04	26 May 2017, 20:15	4.08
8R	29.65	55.11	26 May 2017, 19:00	7.43
9C	95.61	74.04	26 May 2017, 20:15	4.08
8C	29.65	55.11	26 May 2017, 19:00	7.43
4B	114.54	75.55	26 May 2017, 23:30	3.92
3B	65.03	41.98	26 May 2017, 22:30	3.50
11R	275.18	184.04	26 May 2017, 21:45	3.88
5B	87.12	37.53	27 May 2017, 02:45	2.85
12C	362.30	213.74	26 May 2017, 22:45	3.63

(c)

Hydrologic Element	Drainage Area (km^2)	Peak Discharge (m^3/s)	Time pf Peak	Volume (cm)
2B	65.96	35.73	27 May 2017, 00:30	3.22
1B	29.65	63.45	26 May 2017, 19:00	8.52
10R	160.64	136.24	26 May 2017, 21:00	4.62
11C	275.18	199.35	26 May 2017, 21:45	4.18
10C	160.64	136.24	26 May 2017, 21:00	4.62
9R	95.61	87.84	26 May 2017, 20:15	4.87
8R	29.65	63.45	26 May 2017, 19:00	8.52
9C	95.61	87.84	26 May 2017, 20:15	4.87
8C	29.65	63.45	26 May 2017, 19:00	8.52
4B	114.54	69.71	27 May 2017, 00:00	3.56
3B	65.03	51.51	26 May 2017, 22:30	4.26

Continued

11R	275.18	199.35	26 May 2017, 21:45	4.18
5B	87.12	46.53	27 May 2017, 02:30	3.53
12C	362.30	237.20	26 May 2017, 23:00	4.02

(d)

Hydrologic Element	Drainage Area (km^2)	Peak Discharge (m^3/s)	Time pf Peak	Volume (cm)
2B	65.96	22.53	27 May 2017, 01:00	2.05
1B	29.65	47.92	26 May 2017, 19:00	6.48
10R	160.64	93.97	26 May 2017, 21:00	3.20
11C	275.18	153.23	26 May 2017, 21:45	3.24
10C	160.64	93.97	26 May 2017, 21:00	3.20
9R	95.61	62.49	26 May 2017, 20:15	3.43
8R	29.65	47.92	26 May 2017, 19:00	6.48
9C	95.61	62.49	26 May 2017, 20:15	3.43
8C	29.65	47.92	26 May 2017, 19:00	6.48
4B	114.54	63.29	26 May 2017, 23:30	3.30
3B	65.03	34.15	26 May 2017, 22:45	2.87
11R	275.18	153.23	26 May 2017, 21:45	3.24
5B	87.12	30.18	27 May 2017, 03:00	2.30
12C	362.30	176.67	26 May 2017, 22:45	3.02

(e)

Hydrologic Element	Drainage Area (km^2)	Peak Discharge (m^3/s)	Time pf Peak	Volume (cm)
2B	65.96	35.73	27 May 2017, 00:30	3.22
1B	29.65	63.45	26 May 2017, 19:00	8.52
10R	160.64	136.24	26 May 2017, 21:00	4.62
11C	275.18	243.23	26 May 2017, 21:45	5.10
10C	160.64	136.24	26 May 2017, 21:00	4.62
9R	95.61	87.84	26 May 2017, 20:15	4.87
8R	29.65	63.45	26 May 2017, 19:00	8.52
9C	95.61	87.84	26 May 2017, 20:15	4.87
8C	29.65	63.45	26 May 2017, 19:00	8.52
4B	114.54	111.64	26 May 2017, 23:00	5.76
3B	65.03	51.51	26 May 2017, 22:30	4.26
11R	275.18	243.23	26 May 2017, 21:45	5.10
5B	87.12	46.53	27 May 2017, 02:30	3.53
12C	362.30	280.27	26 May 2017, 22:45	4.72

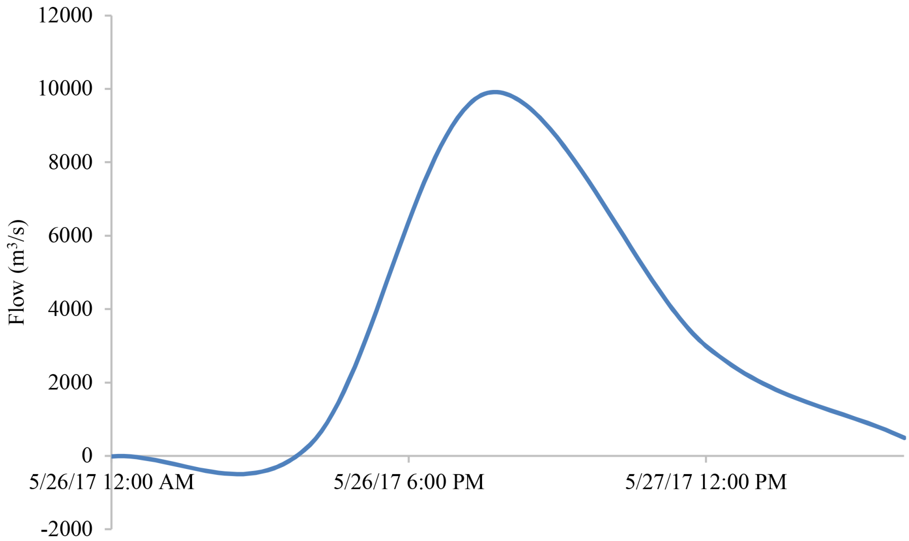

Figure 5. Showing hydrograph at final outlet for scenario-5 (Peak discharge 280.3 m^3/s).

Table 3. Simulated peak discharges and runoff volumes along with percent changes against increasing storm depths and impervious areas in Pipestem Creek watershed.

Scenario	Storm Depth (cm)	Impervious area (%)	Peak discharge (m^3/s)		Runoff volume (cm)		Remarks
			Simulation output	Percent Change	Simulation output	Percent Change	
1	12.34	0	157.30	-	2.69	-	-
2	13.46	0	213.71	35.9	3.63	34.9	Increased
3	14.73	0	237.18	50.8	4.01	49.1	Increased
4	12.34	10	176.64	12.3	3.02	12.3	Increased
5	12.34	20	280.25	78.2	4.72	75.5	Increased

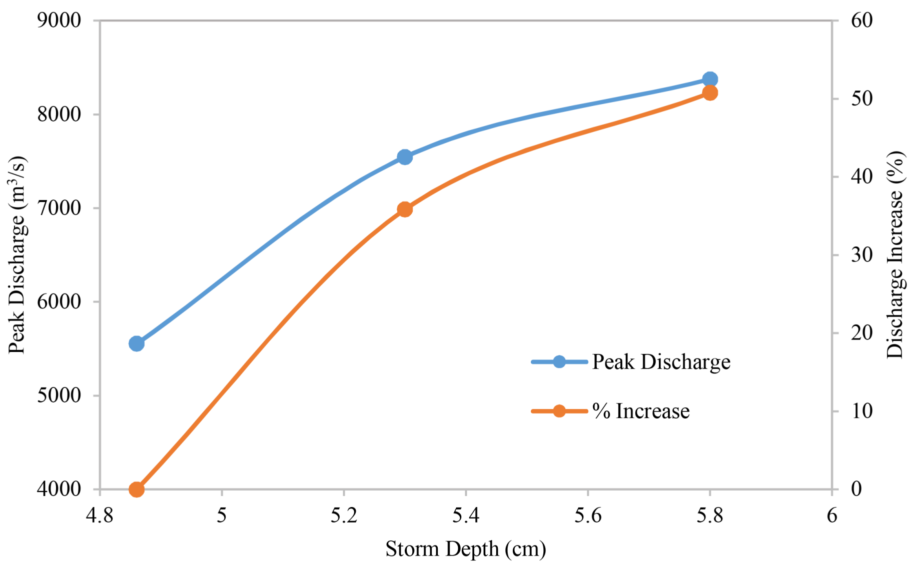

Figure 6. Effect of increasing storm depths on peak discharges.

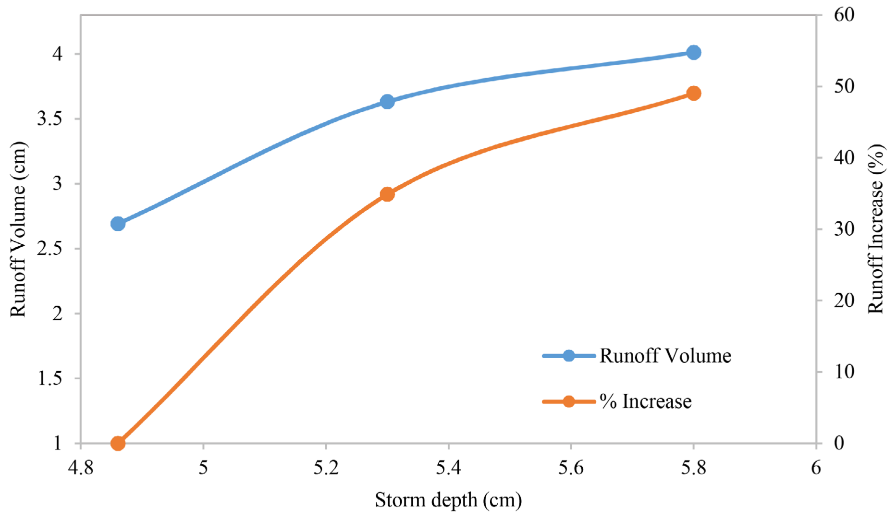

Figure 7. Effect of increasing storm depths on runoff volume.

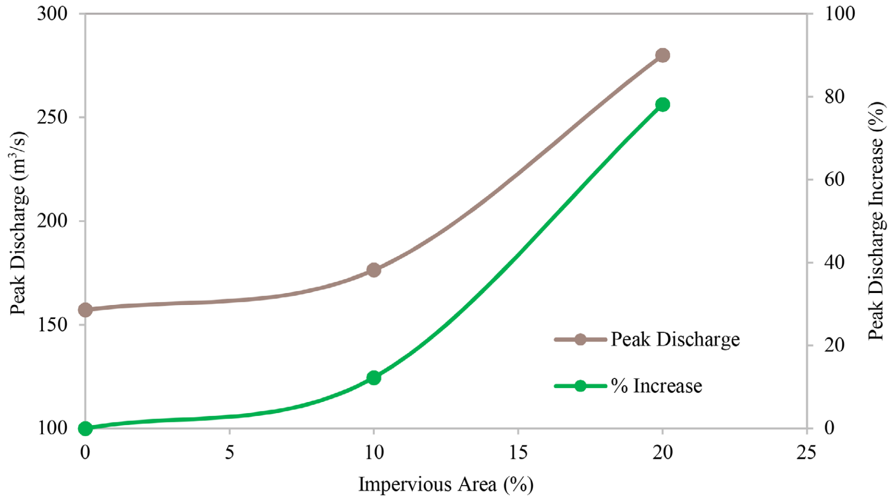

Figure 8. Effect of impervious area on peak discharges.

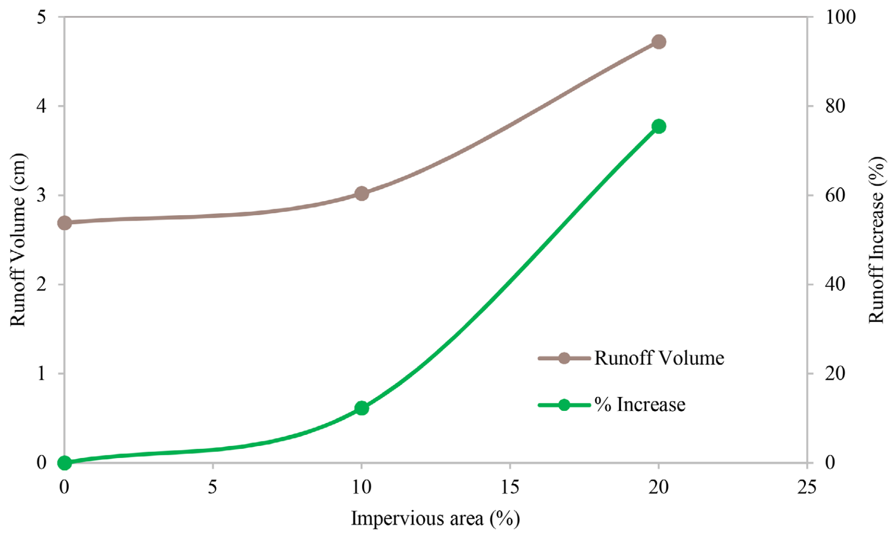

Figure 9. Effect of impervious area on runoff volume.

crease with increasing impervious layers, and runoff volume also showed a positive correlation with increasing impervious layers.

4. Conclusions

A simulation model implemented in the HEC-HMS platform allows for observing the responses due to three increasing rainfall and urbanization scenarios. As expected, the simulation models responded well to increasing rainfall depths and impervious areas. With the change in land use and land cover, the impervious area increases, causing the curve size of the different sub-basins in the area to increase, which will, in turn, cause the peak discharge and runoff volume to increase. When rainfall depths grow to 10% and 20% from the initial rainfall depth, respectively, the peak discharges increased to 36% and 51%. The runoff volumes were increased to 35% and 49%, respectively, for the same scenarios as peak discharges. Peak discharges and runoff volumes both showed similar rising trends as the impervious area increased. Overall, this study demonstrated a correlation between peak flow volume and increasing urbanization or land use pattern of the area.

The study also showed that the prime factor of flow increases from a watershed, land use changes due to urbanization, and industrialization (in terms of impervious areas), had an impact on sub-basin curve numbers. The curve numbers were rising in line with rising urbanization, and as a result, total maximum discharges were rising as well. In brief, the study discovered concrete evidence of an increase in watershed peak discharge with the trend toward urbanization/industrialization. However, this study's limitation was that the current state of water quality was not considered. Since the study showed a connection between the change in land use class brought on by urbanization and industrialization (in terms of impervious areas) and maximum discharge, it is obvious that urbanization will also have an impact on water quality. Future researchers may have the opportunity to focus on this issue.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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